

A Shape-Memory Alloy Thermal Conduction Switch for Use at Cryogenic Temperatures

Final Report

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The following summarizes the activities performed under NASA grant NAG10-323 from September 1, 2002 through September 30, 2004 at the University of Central Florida. A version of this has already been submitted for publication in the international journal *Smart Materials and Structures* in December 2004. Additionally, a version of this has already appeared in print in *Advances in Cryogenic Engineering*, American Institute of Physics, (2004) 50A 26-33 in an article entitled "A Shape Memory Alloy Based Cryogenic Thermal Conduction Switch" by V.B. Krishnan, J.D. Singh, T.R. Woodruff, W.U. Notardonato and R. Vaidyanathan (article is attached at the end of this report). The following presentations have resulted:

- V.B. Krishnan, J. Singh, T. Woodruff, W. Notardonato and R. Vaidyanathan, "A Shape Memory Alloy Based Cryogenic Thermal Conduction Switch: Design, Construction and Materials Development", 41st Space Congress, Cape Canaveral, FL April 27-30, 2004.
- V.B. Krishnan, J. Singh, T. Woodruff, W. Notardonato and R. Vaidyanathan, "A Shape Memory Alloy based Cryogenic Thermal Conduction Switch: Design, Construction and Materials Development", Cryogenic Engineering Conference and the International Cryogenic Materials Conference, Anchorage, AK, September 22-26, 2003.

The activities also significantly formed part of two MS theses at the University of Central Florida:

- V.B. Krishnan, "Design, Fabrication and Testing of a Shape Memory Alloy based Cryogenic Thermal Conduction Switch", defended March 2004
- J.L. Lemanski, "Cryogenic Shape Memory Alloy Actuators for Spaceport Technologies: Materials Characterization and Prototype Testing", April 2005 (expected).

Additionally, two other doctoral students S.B. Shmalo and C.R. Rathod have also benefited but they have been mostly funded by a National Science Foundation (NSF) CAREER award.

Abstract

Shape memory alloys (SMAs) can recover large strains (e.g., up to 8%) by undergoing a temperature-induced phase transformation. This strain recovery can occur against large forces, resulting in their use as actuators. The SMA elements in such actuators integrate both sensory and actuation functions. This is possible because SMAs can inherently sense a change in temperature and actuate by undergoing a shape change, associated with the temperature-induced phase transformation. This work describes the development of an SMA based cryogenic thermal conduction switch for operation between dewars of liquid methane and liquid oxygen in a common bulkhead arrangement for the National Aeronautics and Space Administration (NASA). The design of the thermal conduction switch, based on a biased two-way type SMA actuator, utilizes a commercially available NiTi alloy as the SMA element to demonstrate feasibility of this concept. Such a switch has potential application in variable thermal sinks to other cryogenic tanks for liquefaction, densification, and zero boil-off systems for advanced spaceport applications. The SMA thermal conduction switch offers the following advantages over the currently used gas gap and liquid gap thermal switches in the cryogenic range: (i) integrates both sensor and actuator elements, thereby reducing the overall complexity, (ii) exhibits superior thermal isolation in the open state, and (iii) possesses high heat transfer ratios between the open and closed states.

1. Introduction

Shape memory alloys (SMAs) are superior materials for use as actuators, owing to their ability for temperature-induced strain recovery against large forces [Funakubo 1987, Schetky 1990, Uchino 1998, Vaidyanathan 2002]. SMA actuators can be broadly categorized as one-way and two-way actuators. One-way SMA actuators are used where one-time actuation is necessary such as in safety devices, couplings, etc. In a one-way actuator, the SMA element acts against a force when the temperature reaches a pre-determined value. Two-way actuation can occur either in a biasing mode or a differential mode. The biasing mode uses a bias element opposing the SMA element for actuation in either direction. When the temperature of the SMA element rises to a pre-determined value, the SMA element, being stronger as it undergoes a phase transformation, acts against the bias element and actuates in one direction. As the temperature of the SMA element drops below another pre-determined value, the bias element overcomes the SMA element, and the actuator acts in the opposite direction. Biasing mode operation is more often employed and offers enhanced flexibility in design. In the differential mode of operation, the bias element is substituted by another SMA element. Here actuation in either direction can be achieved by appropriately heating or cooling either of the two SMA elements. Applications requiring precise movement and high accuracy make use of the differential mode [Ohkata & Suzuki 1998].

Ever since the discovery of the shape memory effect in NiTi alloys, they have become the most extensively used SMAs owing to the best combination of material properties they possess [Buehler & Wang 1967, Funakubo 1987 and Duerig & Pelton 1994]. Ordered intermetallic NiTi with near equiatomic composition forms the basis of all NiTi alloys. Close to room temperature, near equiatomic NiTi undergoes a phase

transformation between a monoclinic (B19'), martensite phase and a cubic (B2), parent austenite phase. Some NiTi alloy systems show a martensite-like transformation upon cooling, prior to the martensitic transformation, called an R-phase transformation. Here a transformation from the parent cubic phase (austenite) to a rhombohedral phase occurs. Depending on the composition (either deviating from equiatomic NiTi or substituting a small amount of Ni with another metal) and history of thermomechanical treatments, NiTi alloys exhibit complex phase transformation behaviours. This may include one or more combinations of a shift in transformation temperatures, appearance of intermediate phases and changes in hysteresis. NiTi is fairly sensitive to elemental additions. Addition of Fe, Al, Cr, Co or V (that tend to substitute Ni) depresses the onset of the martensite phase transformation [Goldstein *et al.* 1964]. This depression is strongest with the addition of Cr, while weakest with V and Co. These additions have practical importance in creating cryogenic SMAs, stiffening the austenitic phase, or in increasing the separation of the R-phase from the martensitic one [Duerig & Pelton 1994].

The motivation for this work comes from National Aeronautics and Space Administration (NASA) Kennedy Space Center's (KSC) requirement for thermal management at cryogenic temperatures. The main objective of this project is to design, construct and test an SMA thermal conduction switch to facilitate thermal conduction of approximately 8 watts between two liquid reservoirs held at 118 K and 92 K (boiling points of liquid methane and liquid oxygen, respectively). This switch is expected to control the liquid methane temperature and pressure in a zero boil-off system by allowing on-demand heat transfer between two reservoirs kept at separate temperatures, in an efficient and autonomous manner. Such a switch would support methane liquefaction for future Mars missions in addition to fulfilling immediate requirements at NASA KSC.

The cryogenic range thermal switches that are currently used range from gas gap and liquid gap thermal switches that rely on convective heat transfer between two surfaces to externally actuated thermal switches. The sensors and active controls in such systems make them more complicated and expensive, yet less efficient than the proposed switch. Furthermore, gas gap switches are restricted to long cycle times, tend to exhibit poor thermal isolation in their open state, and have low heat transfer ratios between open and closed states. Other systems using conduction bands make use of mechanical means to generate sufficient thermal contact and may not be reliable. SMA thermal switches have the potential to limit these problems.

2. Design

The initial design concept of the shape memory alloy based cryogenic thermal conduction switch for thermal conduction between a liquid methane reservoir (high-temperature reservoir) kept at 118 K and a liquid oxygen reservoir (low-temperature reservoir) kept at 92 K is shown in Figure 1. The design uses a bias spring in addition to an SMA spring for two-way actuation. The SMA spring (liquid methane side) and bias spring are attached on either side of a moving copper contact. A flexible copper strap that is thermally connected to the moving copper contact is expected to provide a path for heat conduction when the switch is in the closed position (when the moving copper contact comes in thermal contact with the stationary copper contact on the liquid methane side). The SMA

spring, sensing the temperature in the liquid methane tank, will undergo a phase transformation (from martensite to austenite) when the temperature in the liquid methane tank increases above a certain temperature. This phase transformation will be coupled with an increase in its strength that provides a thermal contact between the two copper contacts (moving copper contact and stationary copper contact on the liquid methane side) by working against the bias spring. Indium foils are used between the copper contacts to limit the variation in thermal conductivity with contact force. The conductive heat path thus established through the flexible copper strap results in liquid oxygen cooling liquid methane. When the temperature of the liquid methane tank drops to the specified temperature, the SMA spring will undergo a reverse transformation. This resulting weaker phase (martensite) will not be able to hold the bias spring, thus breaking the heat conduction circuit.

Drony *et al.* in 2003, developed a prototype that successfully demonstrated the feasibility of the concept in a switch that operated between ice water (273 K) and hot water (338 K) using commercially available NiTi. However, the implementation of the concept in a working prototype at cryogenic temperatures needed to address issues such as: (i) hysteresis of the SMA element; (ii) the developing temperature gradient over the length of the SMA element when the switch is in the closed condition; (iii) contact resistance for efficient and reliable heat transfer, as the switch is expected to work in vacuum conditions; (iv) and contact force generated by the SMA element. A final design (Figure 2) was arrived at after considering the aforementioned issues, by positioning both the SMA element and the bias spring on the same side, using insulation at one end of the element, using indium foil between the mating surfaces and by controlling the phase transformation [Krishnan *et al.* 2004]. The design consists of a stationary plate (fixed copper contact) on the methane side, three rods for support and heat transfer, three SMA helical compression springs concentric to the support rods, three spring seats that keep the SMA springs in position and also insulate them from the stationary plate, a bias extension spring placed in between the SMA springs with bias spring holders on both ends, a moving plate (moving copper contact) for actuation, and three bushings fixed to the moving plate for easy sliding on the support rods. The two ends of the bias spring were made straight due to dimensional constraints and for ease of adjustment of the distance between the two plates (stationary and moving plates). The bias spring holders were devised to adjust the length of the bias spring, with two set screws securing the ends of the bias spring. All the materials for the final design were selected keeping in mind issues of low-temperature embrittlement and thermal conductivity. These materials included oxygen free pure Cu for the stationary and moving plates, Be-Cu alloys for the support rods and bushings, austenitic stainless steels containing more than 7% Ni for the bias spring, brass for the bias spring holders and polytetrafluoroethylene (Teflon) for the spring seats. Indium foil and Apiezon[®] N grease were used to enhance the thermal conductivity between mating parts.

Various parameters for the SMA spring were obtained as given below [Waram 1990, Ohkata & Suzuki 1998]. The stress concentration factor, K , was determined from

$$K = [(4C-1) / (4C-4)] + (0.615 / C); \quad (1)$$

the shear stress, τ , was determined from

$$\begin{aligned} \tau &= (8 P D K) / (\pi d^3) \\ &= (8 P C K) / (\pi d^2); \end{aligned} \quad (2)$$

the allowable shear strain, γ_S , was determined from

$$\gamma_S = \gamma_{\max} - \gamma_H; (\gamma_{\max} = 1\%); \quad (3)$$

and the number of turns, n , was determined from

$$n = (\delta d) / (\pi \gamma_S D^2); \quad (4)$$

where, C is the spring index, P is the load on the spring, γ_H is the austenitic shear strain, D is the mean diameter of the coil, d is the diameter of the wire and δ is the maximum deflection. Using the above formulae, Table 1 shows the resulting parameters obtained for the SMA helical springs. Using standard helical spring theory [Vallance & Doughtie 1951, Shigley & Mischke 2000], Table 2 shows the parameters derived for the bias spring.

3. Thermal analysis

The proposed thermal switch is to work between methane and oxygen dewars, each with a capacity of 25 L. Taking the density and specific heat of methane at 118 K to be $424 \text{ kg}\cdot\text{m}^{-3}$ and $3530 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ [McClintock 1984], respectively, a 2 K rise in temperature will require 74.8 kJ of heat. Considering a heat leakage of 2 W, this would take 10.4 hrs. With a single 8 W conduction switch working between the dewars, it would thus take 3.5 hrs (6 W effective cooling capacity) to cool the methane dewar from 120 K to 118 K.

Heat transfer analyses were carried out using TMG simulations of I-DEAS Master Series version 9 (Structural Dynamics Research Corporation). Both steady state and transient analyses were carried out. The objectives of the steady state analysis were to determine the temperature profile of the SMA element and the moving thermal contact when the switch is in the closed position and the temperature of the methane tank is at 120 K. A transient analysis was carried out to study the response time. For this, an assembly model was constructed to represent the actual geometry of the prototype. Finite element meshing was applied to the relevant contact surfaces and on the volume that represented geometrical symmetry. The following assumptions were made: (i) The initial temperature of the assembly is between 119 K and 120 K, (ii) the stationary copper

Table 1. SMA spring design parameters.

Load on each spring	16 N
Deflection	10 mm
Spring index	12
Wire diameter	2.159 mm
Mean coil diameter	25.908 mm
Number of turns	4
Free length of the spring	23.636 mm

Table 2. Bias spring design parameters.

Material for bias spring	Stainless steel AISI 302
Load on the spring	20 N
Deflection	8 mm
Spring index	10
Wire diameter	1.628 mm (AWG 14)
Mean coil diameter	16.280 mm
Number of turns	6
Free length of the spring	9.768 mm

contact is in thermal equilibrium with the methane tank, and (iii) effects of convection and radiation are negligible. A set of boundary conditions (methane tank at 120 K and oxygen tank at 92 K) and thermal properties of the materials at 100 K (for those materials where data was available at 100K) were used in the model.

From the steady state analysis, a temperature gradient of 28 K (maximum of 120 K, minimum of 92 K and average of 108 K) was obtained uniformly throughout the heat transfer cross-section (Figure 3). A response time of 2.5 hrs was obtained from the transient analysis.

4. Fabrication

Given that the application-specific cryogenic NiTi alloy was not commercially available, the SMA elements for the switch were made from commercially available NiTi alloys that had the lowest transformation temperatures. NiTi wire (56.14 wt. % Ni nominal composition, diameter 0.216 cm) with an austenite start temperature of 234 K was obtained from Special Metals Corp., NY. The shape setting was done by confining the NiTi wire in the helical groove of a cylindrical mandrel and then heat treating in a Fisher Isotemp[®] programmable muffle furnace at 673 K for 20 minutes, followed by quenching in ice-water. Due to the initial composition and the form of the material used, and also for ease of heat treatments, subsequent thermal treatments were performed on the NiTi spring to enhance its shape-memory properties. These thermal treatments included a solution treatment followed by an ageing treatment and were carried out under vacuum conditions using a cage with ceramic sleeves in an IVI Corp. vacuum furnace with quenching capability. The cage prevented the SMA spring from changing its shape during the heat treatment. Solutionizing was done at 1073 K for 2 hours followed by an oil quench to room temperature. Ageing was done at 934 K for 1 hour followed by an oil quench to room temperature. The ageing treatment at high temperatures (> 773 K) followed by quenching inhibits the formation of Ni-rich precipitates, which will ensure a lower austenitic transformation range. If aged at 673 K, the NiTi decomposes into a Ti-rich matrix composition with a higher austenitic start temperature, together with a Ni-rich phase finely dispersed in it [Melton, 1990]. Furthermore, ageing at higher temperatures suppresses the R-phase transformation and superelasticity in Ni-rich binary alloys.

Dilatometric measurements of transformation temperatures were made on the SMA spring prepared by shape setting before and after the thermal treatments (Figure 4). Table 3 shows a comparison of transformation temperatures obtained from both dilatometric measurements. The subscripts S,F and P stand for start, finish and peak temperatures, respectively, corresponding to the austenite (A) and martensite (M) phase transformations. It was observed that subsequent thermal treatments lower the transformation temperatures significantly. Furthermore, the hysteresis was reduced by 25 K. The fact that the ageing treatment was done at a high temperature (> 773 K) and was followed by quenching ensured a lower austenitic transformation range.

Table 3. Effect of the thermal treatments on transformation temperatures.

	Thermal Treatment	
	Before	After
M_s	273 K	253 K
M_f	213 K	193 K
A_s	283 K	237 K
A_f	321 K	285 K
M_p	~ 243 K	~ 213 K
A_p	~ 303 K	~ 248 K
Hysteresis	~ 60 K	~ 35 K

The SMA spring was tested to determine its stiffness after the thermal treatments under austenitic (room temperature) and martensitic (liquid nitrogen temperatures) conditions. The spring rate obtained was 1.7180 N/mm for the austenitic spring and 0.2108 N/mm for the martensitic spring. Figure 5 shows the force versus deflection of the bias spring (a third of the actual stiffness) and the SMA spring under austenitic and martensitic conditions. The bias force is one-third that of the original stiffness of the bias spring because a single bias spring opposes three SMA springs in the final design. Since the bias spring opposes the SMA springs, their respective slopes have opposite signs. It can be seen from the graph that the bias spring would be additionally extended by about 10 mm, by the SMA spring in the austenitic condition than in the martensitic condition. Thus, if the switch is compressed in hot conditions by about 5 mm, a contact force of about 36 N can be generated.

5. Testing

The switch was tested for actuation and determining the contact force in order to assess the problem of contact resistance encountered in vacuum and cryogenic systems. The switch was actuated in an argon controlled atmosphere in a cryogenic setup that simulated the original requirements (hereafter referred to as "inside chamber actuation") and the contact force was measured using a setup in ambient air (hereafter referred to as "outside chamber actuation"). The inside chamber actuation resulted in a deflection of about 3 mm (Figure 6 a,b) during the martensitic phase transformation of the SMA elements. The outside chamber actuation recorded a deflection of 6.543 mm without any external load and 3.610 mm with an external load of 20 N. Figure 7 shows deflection as a function of temperature during outside chamber actuation with and without an external load of 20 N. There is a difference of 7 K for the onset of austenitic transformation.

6. Discussion

During inside chamber actuation, a temperature gradient was evident from the pattern of martensitic deformation in the SMA springs (Figure 6b). There was a gradual variation in the spacing between the SMA spring loops, the closest being near the moving plate side and the farthest at the opposite end. When such a thermal gradient develops, the transformation to martensite may not be uniform, resulting in fully transformed martensite at the moving plate end and more untransformed austenite at the other end. Thus, keeping the SMA element parallel to the conduction path creates a temperature gradient within the element (whatever the counter measures are). This may be avoided by designing the actuator with an alternate conduction path. Again, it is preferable to sense the temperature fluctuations within the methane dewar rather than depend on the fluctuation during the heat transfer that takes place between the oxygen and methane dewars. A patent is currently being pursued for a design with these two approaches in mind.

The actuation of the prototype was observed at a larger temperature difference between the two reservoirs than the required value of 28 K, the problem arising due to limitations in tailoring transformation temperatures in a commercially available cryogenic SMA (NiTi) material. The martensitic hysteresis in SMAs is a major problem in designing an actuator that is supposed to work within a limited temperature range. This problem can be addressed in at least two ways: (a) Use of R-phase transformation (between austenitic phase and R-phase) that is coupled with a temperature hysteresis as low as 1.5 K. Strains are limited to less than 1 %, but have higher fatigue life than martensitic transformation. (b) A combination of thermo-mechanical treatments on a suitable NiTi alloy (tailoring the composition by the addition of a third element). Associated with the issue of a wider hysteresis, is the issue of tailoring the phase transformation to occur at around 118 K. Again, the aforementioned approach of tailoring the composition with ternary elemental additions and thermomechanical treatments is suggested and is currently being pursued.

The heat transfer rate was 11.94 W for a temperature difference of 52 K. This scales down to a heat transfer rate of around 6.5 W for a temperature difference of 28 K that is comparable to the required 8 W. Additionally, when the loss factors due to convection were taken into account, the heat transfer rate was closer to 8 W. The SMA switch was able to support an external load of 20 N for a difference in deflection of 2.933 mm during outside chamber actuation. It is worth noting that a load of 20 N is sufficient to obtain good thermal contact between copper conductors separated with indium foil, even at liquid helium temperatures [Salerno & Kittel 1998]. The difference in deflection of 2.933 mm that was observed with an external load of 20 N when extrapolated for a deflection of 5 mm gives a load of 34.13 N. The value of 34.13 N is in reasonable agreement with the value of 36 N projected from Figure 5 and previously discussed. The temperature difference of 7 K for the onset of austenitic transformation was expected as the presence of additional stress (in addition to stress from the bias spring) delays the transformation of martensite to austenite.

7. Conclusions

The design and development of a SMA based cryogenic thermal conduction switch for operation between dewars of liquid methane and liquid oxygen in a common bulkhead arrangement has been presented. Such a switch integrates the sensor element and the actuator element and can be used to create a variable thermal sink to other cryogenic tanks for liquefaction, densification, and zero boil-off systems in advanced spaceport applications. The design of this thermal conduction switch is based on a biased, two-way SMA actuator. This work describes the design, from concept, of a cryogenic SMA thermal conduction switch. A finite element based thermal analysis was carried out to predict the behaviour of the thermal conduction switch. SMA springs were made from a commercially available NiTi SMA wire that had the lowest transformation temperatures and various heat treatment processes were carried out on them to enhance their performance. An SMA thermal conduction switch using these SMA helical springs was effectively fabricated and was tested at cryogenic conditions. Successful actuation was achieved within the limitations of the commercially available cryogenic SMA material and conditions. The experience from this work resulted in recommendations for future improvements in the use of SMA materials and design. Work is ongoing to further reduce the operating temperature of such a switch by recourse to using custom cast NiTi SMAs with ternary element additions and appropriate thermomechanical processing.

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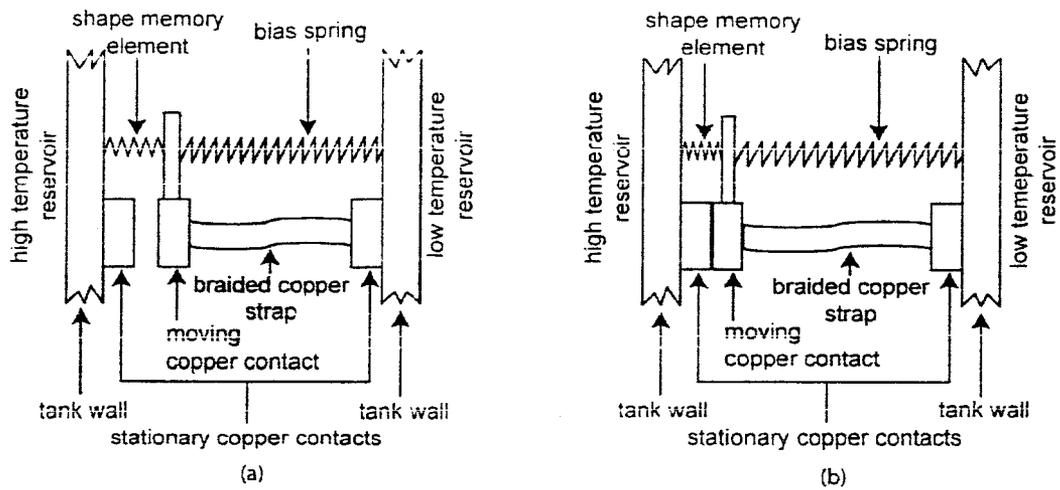


Figure 1. Schematic illustrating the concept for a shape memory alloy based cryogenic thermal switch in the (a) open position and (b) closed position.



Figure 2. Shape memory alloy based cryogenic thermal switch.

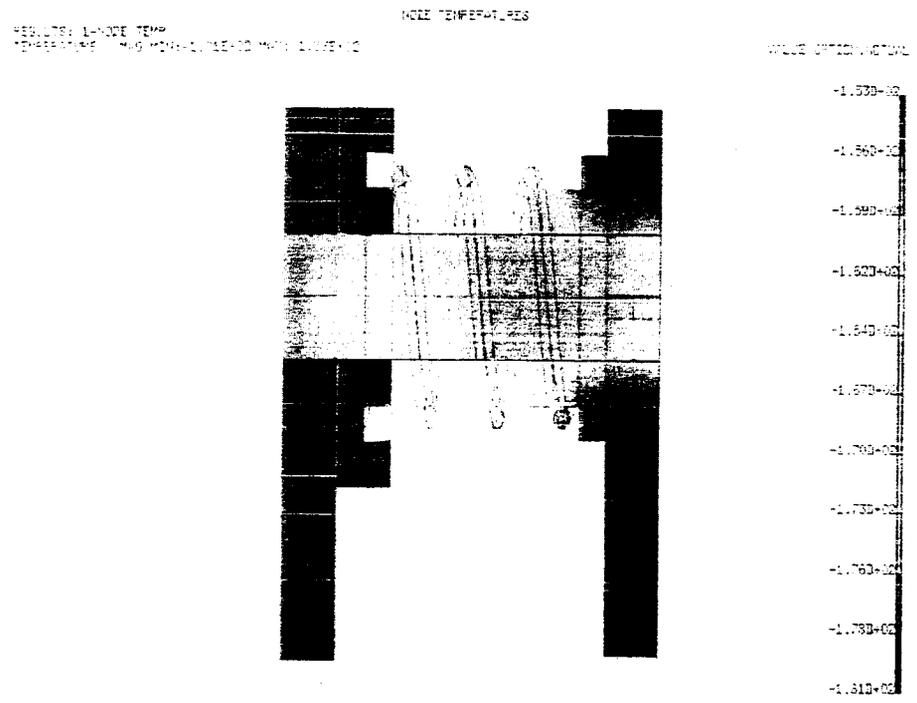


Figure 3. The temperature profile of the heat transfer cross-section obtained during steady state finite element analysis using I-DEAS.

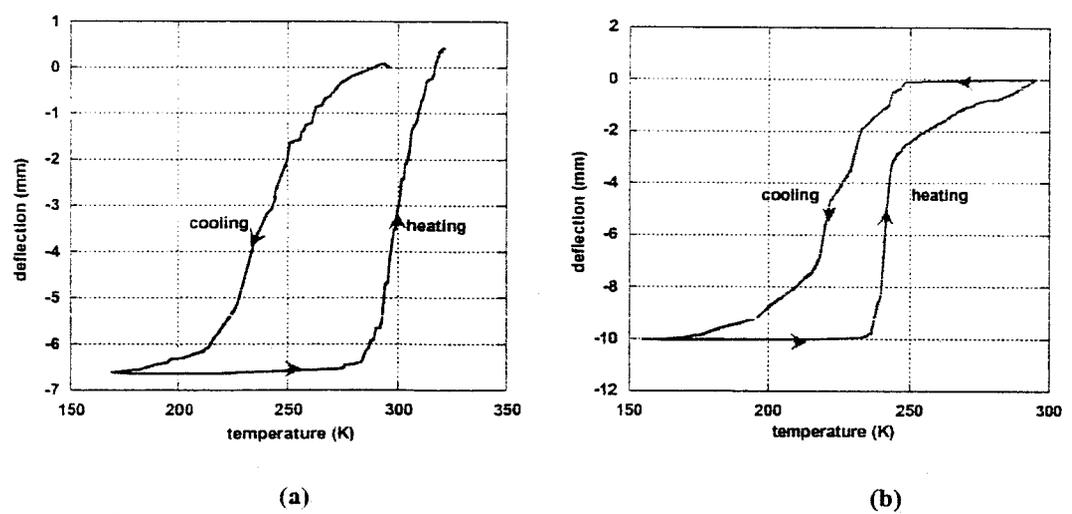


Figure 4. Deflection vs. temperature of the SMA spring: (a) before the thermal treatments and (b) after the thermal treatments.

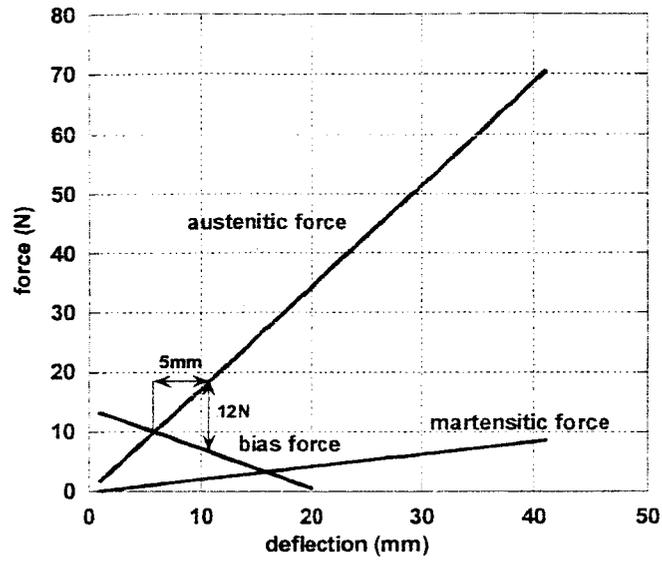


Figure 5. Force as a function of deflection for the bias spring and the SMA spring in austenitic and martensitic conditions.

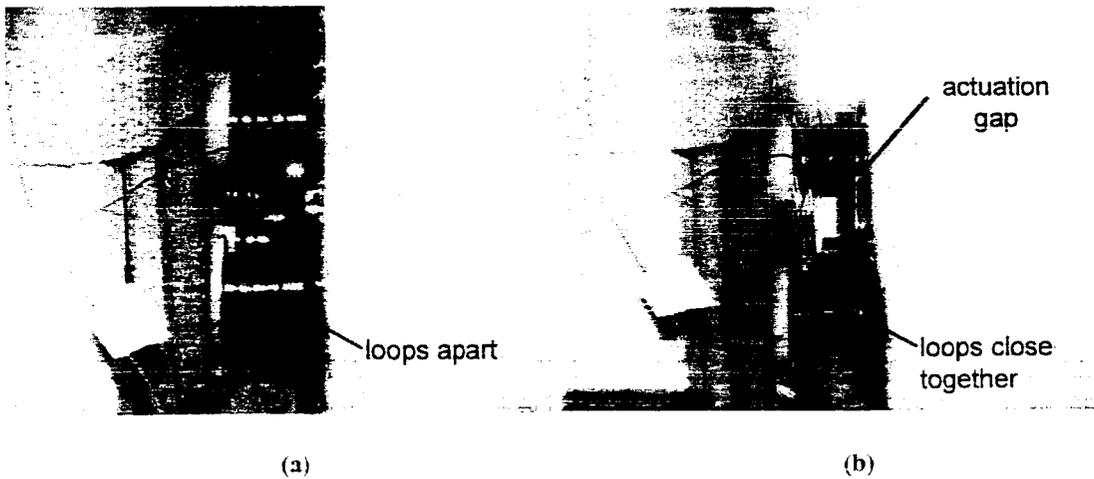


Figure 6. SMA thermal switch (a) before actuation and (b) during actuation.

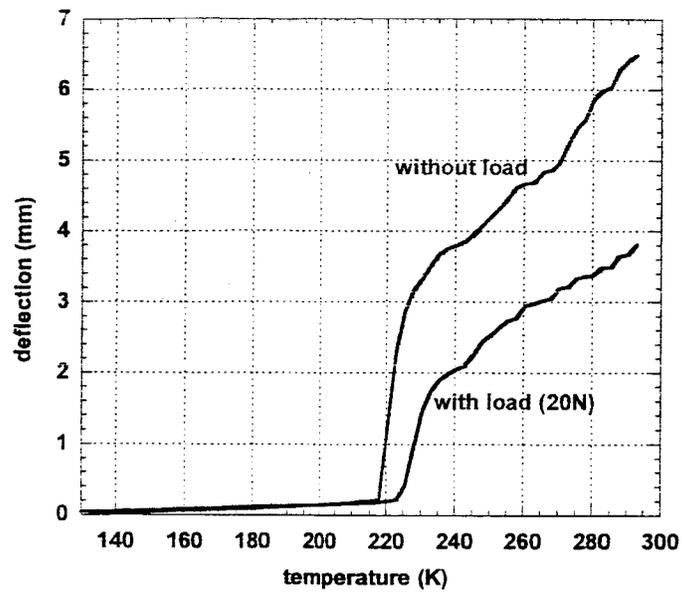


Figure 7. Deflection as a function of temperature during outside chamber actuation, with and without external load.

A SHAPE MEMORY ALLOY BASED CRYOGENIC THERMAL CONDUCTION SWITCH

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ABSTRACT

Shape memory alloys (SMAs) can produce large strains when deformed (e.g., up to 8%). Heating results in a phase transformation and associated recovery of all the accumulated strain. This strain recovery can occur against large forces, resulting in their use as actuators. Thus an SMA element can integrate both sensory and actuation functions, by inherently sensing a change in temperature and actuating by undergoing a shape change as a result of a temperature-induced phase transformation. Two aspects of our work on cryogenic SMAs are addressed here. First - a shape memory alloy based cryogenic thermal conduction switch for operation between dewars of liquid methane and liquid oxygen in a common bulkhead arrangement is discussed. Such a switch integrates the sensor element and the actuator element and can be used to create a variable thermal sink to other cryogenic tanks for liquefaction, densification, and zero boil-off systems for advanced spaceport applications. Second - fabrication via arc-melting and subsequent materials testing of SMAs with cryogenic transformation temperatures for use in the aforementioned switch is discussed.

INTRODUCTION

Shape memory alloys (SMAs) when deformed can produce strains as high as 8%. Heating results in a phase transformation and associated recovery of all the accumulated strain, a phenomenon known as the shape memory effect. Thus SMAs are a unique class of alloys that "remember" and return to their original shape due to a thermally-induced phase transformation, following deformation. The strain recovery can occur against large forces, resulting in their use as actuators [1-4]. This principle is schematically shown in FIGURE

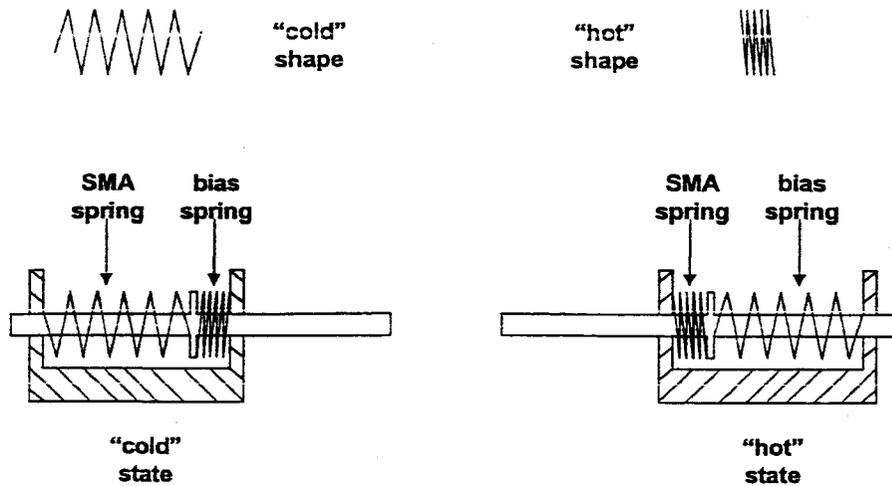


FIGURE 1. The shape memory effect and a simple switch based on this effect.

1. When the SMA element is exposed to an increase in temperature, it undergoes a phase transformation. Associated with this phase transformation is a shape change that constitutes the actuator displacement and can occur against an external force (e.g., a bias spring). Once the temperature returns to the initial level, the new phase is no longer stable and reverts to the original phase. This original phase being more compliant deforms easily and is now overcome by the bias spring. Potential applications include - flaps for directing airflow in air-conditioners, thermal switches for controlling coolant in automobiles, air dampers for multi-function electric ovens, thermal mixing valves in faucets, etc.

SMA actuators are particularly advantageous for space applications in that: (i) They integrate sensory and actuation functions. The SMA element inherently senses a change in temperature and actuates by undergoing a shape change as a result of a phase transformation. Consequently, the need for external electronic sensors and control is eliminated. (ii) They function in clean, debris-less, spark-free manner. The shape change that is responsible for the actuator displacement is again an inherent material property. It is not associated with moving parts that require lubrication or electrical signals with a potential to spark. (iii) They have high power/weight and stroke length/weight ratios. The operating range includes strain and stress limits of 8% and 700 MPa, respectively, depending on the number of required cycles. (iv) They possess the ability to function in zero-gravity environments with small, controlled accelerations. The displacement strains are a result of a thermally-induced phase transformation which can be controlled by the heat transfer rate (e.g., appropriate insulation).

The phase transformation that is usually responsible for strain recovery in SMAs is a reversible thermoelastic martensitic transformation. For example, in near equi-atomic NiTi the high temperature phase is a cubic (B2) austenitic phase while the low temperature phase is a monoclinic (B19') martensitic one. There is a temperature hysteresis associated with the forward and reverse transformations that ranges from 10-15 K for NiTiCu alloys, to 20-60 K for binary NiTi alloys, to 100 K for NiTiNb alloys [5,6]. Certain alloys also exhibit an intermediate rhombohedral or R-phase transformation that is associated with a much lower transformation hysteresis, e.g., 1.5-2 K. The transformation temperature hysteresis depends on factors such as alloy composition, thermo-mechanical treatment, thermal cycling and external loading.

While several alloy systems have been found to exhibit the shape memory effect, only those alloys that recover considerable amount of strain or can overcome substantial force

during recovery are of commercial importance. These include NiTi alloys (Nitinol) and copper-based alloys such as CuAlNi and CuZnAl. Of these, NiTi-based alloys have found considerable use as actuators and in biomedical applications. NiTi is fairly sensitive to alloy element additives. Addition of Fe, Al, Cr, Co or V (that tend to substitute Ni) depresses the onset of the martensite phase transformation [7]. This depression is strongest with the addition of Cr, while weakest with V and Co. Their additions have practical importance in creating cryogenic SMAs, stiffening the austenitic phase, or in increasing the separation of the R-phase from the martensitic one [6].

OBJECTIVE

The objective here was to design, construct and test an SMA thermal conduction switch (actuator) to facilitate thermal conduction of approximately 8 watts between two liquid reservoirs held at 118 K and 92 K. Such a switch would control the liquid methane temperature and pressure in a zero boil-off system by allowing on demand heat transfer between two reservoirs kept at separate temperatures in an efficient and autonomous manner. It would also support methane liquefaction for future Mars missions in addition to fulfilling immediate requirements at NASA-Kennedy Space Center. Gas gap and liquid gap thermal switches that rely on convective heat transfer between two surfaces are currently being used as cryogenic range thermal switches. The sensors and active controls in such systems make them further complicated and expensive, yet less efficient than the proposed switch. Other systems using conduction bands make use of mechanical means to generate sufficient thermal contact and may not be reliable. SMA thermal switches have the potential to limit these problems.

CONCEPT

The initial design concept of the thermal conduction switch is shown in FIGURE 2. The design uses a bias spring in addition to an SMA spring for two-way actuation. A flexible copper strap provides the path for heat conduction when the switch is in the closed position. The SMA spring, sensing the temperature in the liquid methane tank, undergoes a phase transformation when the temperature in the liquid methane tank increases above a

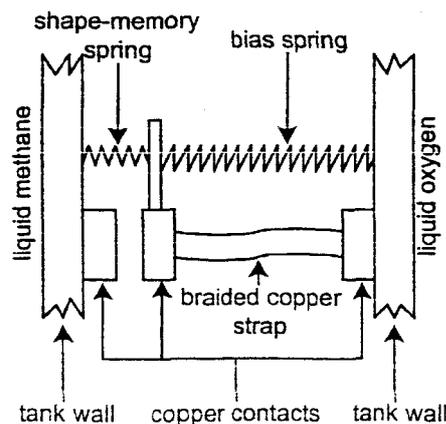


FIGURE 2. Concept for a shape memory alloy based cryogenic thermal switch.

certain temperature. This phase transformation results in an increase in the SMA spring's stiffness, overcomes the bias spring and provides thermal contact between the two copper contacts. Indium foils are used between the copper contacts to limit the variation in thermal conductivity with contact force. The conductive heat path thus established through the flexible copper strap results in the liquid oxygen cooling the liquid methane. When the temperature of the liquid methane tank drops to the specified temperature, the SMA spring undergoes the reverse phase transformation. The resulting phase is more compliant and is overcome by the bias spring, thus breaking the heat conduction circuit.

HEAT TRANSFER ANALYSIS

In order to determine the feasibility of the concept, finite element thermal analyses were carried out using TMG simulations in I-DEAS Master Series version 9 (Structural Dynamics Research Corporation). Both steady state and transient analyses were carried out. The objective of the steady state analysis was to determine the temperature profile of the SMA element and the moving thermal contact when the switch is in the closed position (i.e., when thermal contact is made) and the temperature of methane in the tank is above the required holding temperature. The transient analysis was carried out to study the response time.

An assembly model was constructed and meshed to represent the geometry of the prototype discussed in the next section. The stationary copper contact was assumed to be in equilibrium with the methane tank and the effects of convection and radiation were ignored. The initial temperature of the assembly was arbitrarily set between 119 K and 120 K, the methane tank at 120 K and the oxygen tank at 92 K. The steady state gradient in the SMA element was relatively uniform with an average temperature of 108 K. The transient response gave a response time of 2.5 hrs. The feasibility of the target goal of 8 W was also confirmed. Thus a heat leak of 2 W in a 25 L dewar resulted in methane gaining 2 K in about 10.4 hours while the liquid oxygen needed 3.5 hours to cool the methane by 2 K. An important output of the thermal analyses was that attention had to be paid in the placement of the SMA element relative to the oxygen tank.

IMPLEMENTATION

The aforementioned concept was implemented in two prototypes. The first prototype successfully demonstrated the feasibility of the concept in a switch that operated between ice water (273 K) and hot water (338 K) using commercially available NiTi and is outlined in Ref. [8]. Another prototype was fabricated for testing in cryogenic vacuum conditions and incorporated SMA elements in spring forms. Various issues that were addressed in the design of the thermal conduction switch included: (i) hysteresis of the SMA element; (ii) the developing temperature gradient over the length of the SMA element when the switch is in the closed condition; (iii) contact resistance for efficient and reliable heat transfer, as the switch is expected to work in vacuum conditions; (iv) and contact force generated by the SMA element. These issues were respectively addressed by positioning both the SMA element and bias spring on the same side, using insulation at one end of the element, using indium foil between the mating surfaces and by controlling the phase transformation.

Two approaches were used to fabricate the SMA elements. The first relied on commercially available SMA alloys and consequently did not have optimal transformation temperatures. The second relied on the development of ternary cryogenic NiTiFe alloys and

is discussed in the next section. All the materials for the construction of the prototype were selected by keeping in mind issues of low-temperature embrittlement and thermal conductivity. These materials included pure copper, brass, beryllium-copper alloys, austenitic stainless steels containing more than 7% nickel and polytetrafluoroethylene (Teflon). Furthermore, indium foil and Apiezon[®] N grease were used to enhance the thermal conductivity between mating parts. The fabrication of the SMA elements involved shape-setting and subsequent heat treatments. Shape-setting of an SMA element refers to the process of setting the original or parent shape that the element will return to on heating. Shape setting is done by constraining the SMA element into a required shape using a fixture or mandrel and then heating it to temperatures of around 673 K to 773K for 1 to 20 minutes depending on the size of the element. Following SMA spring theory [9,10], 0.216 cm diameter NiTi wire (56.1 wt.% Ni nominal composition) was set into 3 coils, with each coil being 2.6 cm in diameter, in order to obtain a maximum recovery force of 16 N and a stroke of 1 cm. The shape setting was carried out at 673 K for 20 minutes. Subsequent heat treatments included a solution treatment followed by an ageing treatment. Solution treatment was done in a vacuum at 1073 K for 2 hours followed by quenching in oil. Ageing treatment was done in a vacuum at 973 K for 1 hour followed by quenching in oil. The lowest transformation temperature (peak) achieved as a result of the heat treatment was 213 K with a hysteresis of 35 K. The NiTi springs were subsequently tested for stiffness in the hot and cold conditions. The results are shown in FIGURE 3. From the values of stiffness in the hot and cold states, the stiffness of the bias spring was calculated for the deflection required [9,10]. The prototype is shown in Figure 4, while the technical specifications and testing results are forthcoming in Ref. [11].

CRYOGENIC SHAPE MEMORY ALLOY DEVELOPMENT

The thermal treatments of commercially available NiTi shape memory alloys in the preceding section were optimized to obtain the lowest transformation temperatures. However, the lowest transformation temperatures achieved did not meet requirements for the switch. Consequently, an effort is ongoing by the authors to develop cryogenic NiTiFe

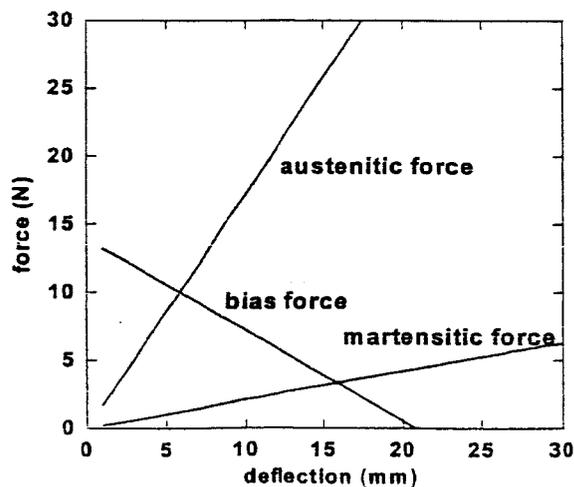


FIGURE 3. Deflection as a function of force for the bias spring and the NiTi spring in hot (austenitic) and cold (martensitic) conditions.



FIGURE 4. A prototype shape memory alloy based cryogenic thermal switch.

shape memory alloys for the thermal conduction switch presented here.

Previously, NiTiFe based shape-memory alloy couplings were widely used to connect titanium hydraulic tubing in Grumman F-14 aircrafts. Given the operating temperature of these aircrafts, the couplings were deformed and stored in liquid nitrogen (77 K). At the time of application, a coupling was introduced to join two tubes at room temperature. The increase in temperature resulted in a phase transformation (at around 120 K) and the shape change associated with the phase transformation decreased the coupling diameter. This decrease in diameter exerted a stress on the tubes and resulted in a secure joint.

The approach to develop a cryogenic NiTiFe shape memory alloy for use in the thermal conduction switch presented here relies on varying the alloy composition. Additionally, the narrow hysteresis rhombohedral or R-phase transformation is being used. High purity powders of Ni, Ti and Fe in varying ratios are thoroughly mixed in a ball mill. Small buttons weighing 0.010 to 0.025 Kg are then made from the blended powders by arc-melting in an IVI Corp. Mark-14 Vacuum/controlled atmosphere furnace (see FIGURE 5a). The resulting buttons (FIGURE 5b) are then thermo-mechanically processed to produce strips that are shown in FIGURE 5c. The strips are tested for their transformation temperatures using dilatometry and differential scanning calorimetry. FIGURE 6 demonstrates the shape memory effect in an alloy processed via the aforementioned route. A clamp weighs down the NiTiFe strip when it is dipped in liquid nitrogen (FIGURE 6a). As the setup warms up to room temperature, the phase transformation results in it straightening out (FIGURE 6b). The stress due to the transformation overcomes 45 MPa in this case.

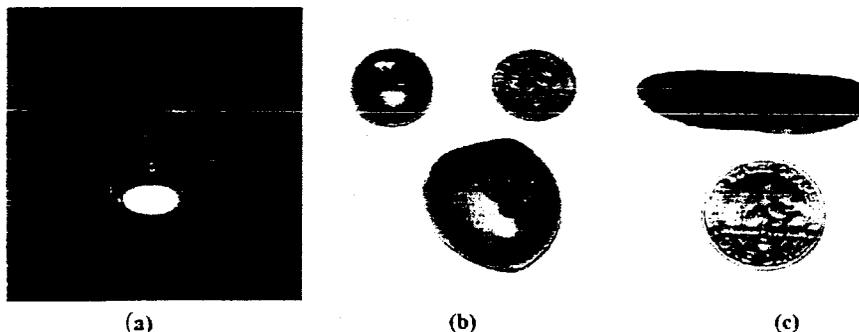


FIGURE 5. Processing of NiTiFe alloys. Arc melting of NiTiFe powders in (a) to form buttons in (b) which are subsequently thermo-mechanically processed to give elements in (c). Such a strip element is tested in FIGURE 6.

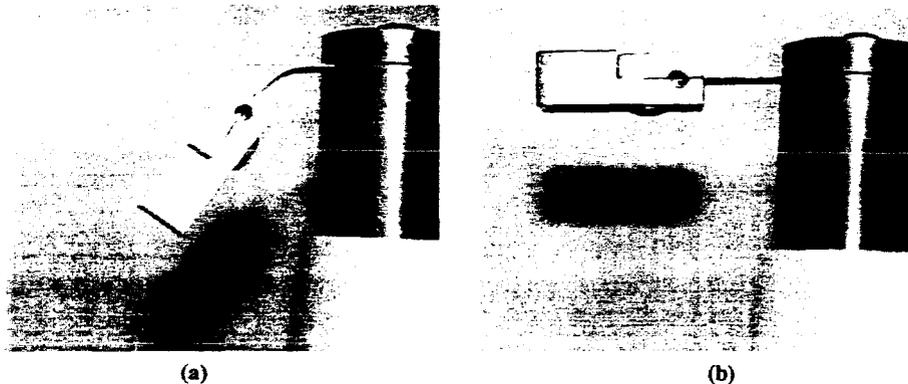


FIGURE 6. Demonstration of a cryogenic shape memory actuator.

CONCLUSIONS

The concept and prototype for a shape memory alloy based cryogenic thermal conduction switch for operation between dewars of liquid methane and liquid oxygen in a common bulkhead arrangement has been presented. Such a switch integrates the sensor element and the actuator element and can be used to create a variable thermal sink to other cryogenic tanks for liquefaction, densification, and zero boil-off systems for advanced spaceport applications. Work is ongoing to develop a cryogenic shape memory alloy that meets the required transformation temperatures and can be implemented in a prototype switch. To date a total of 21 compositions and heat treatments have been attempted with significant knowledge gained on the relationship between transformation temperatures, composition and thermo-mechanical processing. The cryogenic alloys developed have potential use as shape-memory alloy actuator elements for seals, valves, debris-less separation mechanisms, latch and/or release mechanisms, fluid-line repair and self-healing gaskets.

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